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TD - 03 - 053
December 16, 2003

A Preliminary Literature Review of Superconductor and Insulation Behavior under High Radiation Environments

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This report, prepared as a part of the presentation at 43rd workshop on *Super Magnets for Supercolliders* held at Erice (Italy) in October 2003, is a review of work done by several people at various laboratories including Fermilab. I have taken every care to cite the work that has been included in this report. If I have inadvertently missed, I apologize. Furthermore, this report is by no means an exhaustive review of the literature.

Before we go any further, I think it is good to point out the expected radiation dosage in various proposed machines – ITER design specification is equivalent to neutron fluence levels of 1 x 10^{18} n/cm^2 (E > 0.1 MeV) and a dose of 47 MGy [1]. For LHC IR quadrupole coils, it is 10^{16} n/cm^2 (E > 0.1 MeV) and 22.5 MGy over first 10 years with luminosity profile defined in [2]. For 2nd generation LHC IR quads or LARP IR quads it is 2.08 x 10^{16} n/cm^2 (E > 0.1 MeV) and 45 MGy integrated the same way [2-3]. Note that LHC IR quadrupoles have less neutron fluence levels, but have similar 10-yr dose levels as ITER.

The materials that make up the coil are most susceptible to the radiation damage. They include, the superconductor, cable insulation, coil end-parts and depending on the magnet technology the potting compound. The rest of the magnet structure is made up of mostly metals that have much higher radiation resistance.

1.0 Superconductor

NbTi and Nb_3Sn are the most common superconductors used in the magnets. Both show reduction in transport parameters with irradiation. Figs. 1 and 2 illustrate the variation of Ic as a function of neutron fluence in an applied field of 40 kG [4]. For NbTi, reduction in Ic was observed for fluences greater than 3 x 10^{17} n/cm^2 and saturation at 18% was observed for fluences above 3 – 4 x 10^{19} n/cm^2 [4]. For Nb_3Sn, little or no reduction in Ic was observed for neutron fluence below 10^{18} n/cm^2; however, there is an apparent threshold where a rapid reduction in Ic was seen [4].

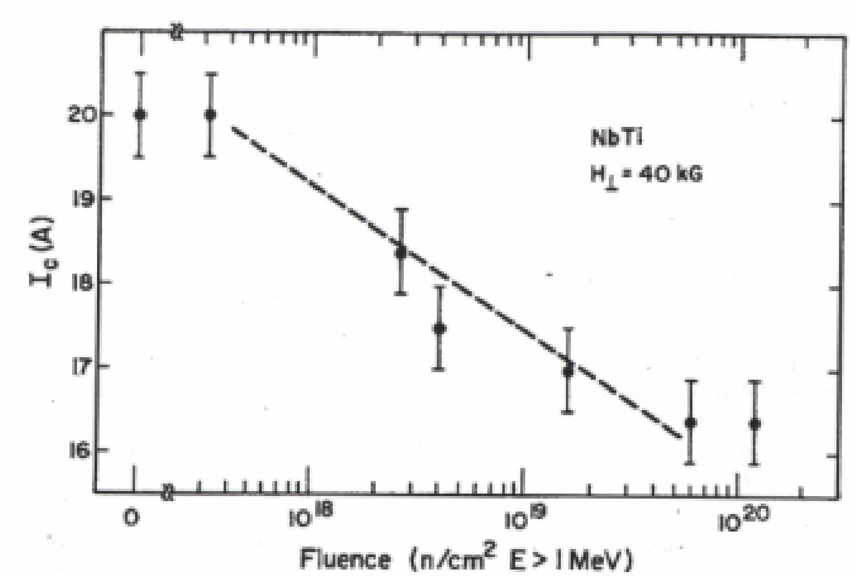

Fig. 1: *Ic (at 40 kG and 4.2 K) as a function of fast neutron fluence for NbTi [4]*

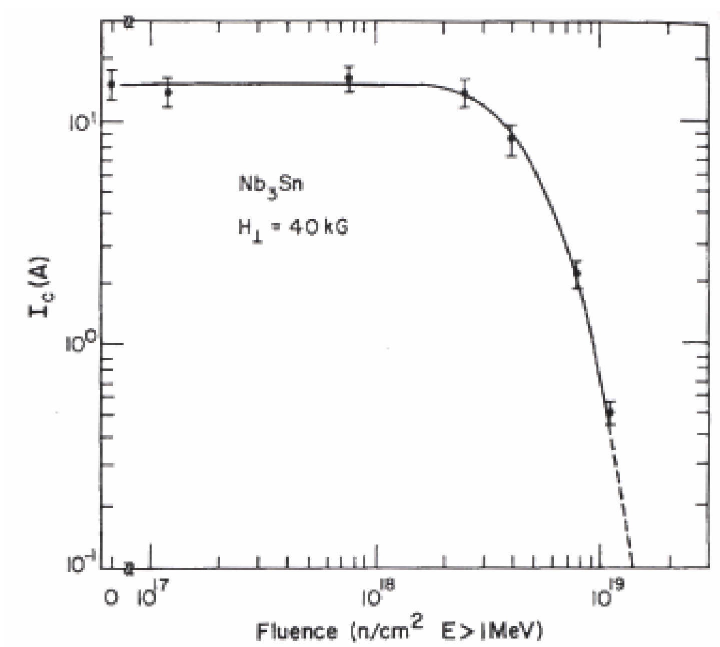

Fig. 2: *Ic (at 40 kG and 4.2 K) as a function of fast neutron fluence for Nb_3Sn [4]*

2.0 Cable Insulation

NbTi cable is typically insulated with Kapton® – a polyimide tape that has high radiation resistance.

Various insulation materials have been used for Nb_3Sn depending on the magnet technology. For wind-and-react technology, S2 fiberglass (in sleeve and tape form) [LBL, University of Twente and Fermilab], Ceramic tape [Fermilab] and quartz tape [SLAC] have been used to insulate the cable. All these materials are known to have good radiation resistance. Note that Kapton® cannot be used as insulation for this technology as the coil has to undergo heat-treatment at temperatures as high as 650 ^{o}C. On the other hand, for react-and-wind technology, Kapton and E-glass have been used as cable insulation [Fermilab and BNL]. All these materials are known to have high radiation resistance.

3.0 Coil End-Parts

Current LHC IR quads have G-11 end-parts that limit the magnet lifetime to about 7 years at a nominal luminosity of 10^{34} cm^{-2}s^{-1}. The magnet lifetime will be further reduced if the highest possible machine luminosity was considered.

For Nb_3Sn magnets, metallic end-parts are typically used in order to sustain high reaction temperatures. This puts higher demand on cable insulation, but from radiation prospective, this should not limit the magnet lifetime or performance.

4.0 Impregnation Medium

Most of the Nb_3Sn magnets made thus far were impregnated with epoxy that has low radiation resistance. Ultimate tensile strength of fiber-reinforced epoxy laminates degrades by up to 36% after irradiation to 1 x 10^{22} n/m^2 (E > 0.1 MeV). Alternate materials for vacuum impregnation have to be investigated in order to improve the radiation resistance of the coil, thus increasing the magnet lifetime. I will try to briefly summarize some of the research that has been done in this area –

4.1 ITER coil insulation R&D Program

Several different potting compounds were analyzed for this program and the following is the summary –

- G-11 CR essentially became unusable at the radiation dose levels of 2.3 x 10^8 Gy. Note that neutron fluence levels of 1.0 x 10^{21}, 1.0 x 10^{22}, 5.0 x 10^{22} m^{-2} (E > 0.1 MeV) translate to total absorbed dose levels (neutron + gamma) of 4.7 x 10^6, 4.7 x 10^7, 2.3 x 10^8 Gy [5].
- The shear strength of some modified epoxy resins such as CTD 101K retained nearly 80% of its strength at radiation dose level of 4.7 x 10^6 Gy and 45% of its strength at 2.3 x 10^8 Gy [5, 6].
- The shear strength of bismaleimide system dropped by 38% at 2.3 x 10^8 Gy [5].
- Polyimide system sustained least damage due to irradiation – the strength remained almost constant with irradiation [5].

4.2 Cyanate Esters

JPL/NASA's work on the precision Segmented Reflector / Telescope Technology program conducted studies in 1992 on different resins that offer good radiation resistance for bonding the panels [7]. The study identified EX-1515, a commercially available cyanate ester resin with 121 ^{o}C cure temperature as a potential candidate. Irradiation tests showed that the flexural strength of EX-1515 dropped from 130 MPa to 104 MPa for a radiation dose of 10^7 Rads.

More recently CTD Inc. in USA and Atomic institute in Vienna are collaborating in developing and testing various cyanate ester based hybrid resins [1,8]. Figs. 3 and 4 show effect of irradiation on shear strength and fatigue properties respectively for CTD-422, a cyanate ester/epoxy blend. Shear strength of CTD-422 drops slightly at lower dose levels where as at the final dose, irradiation leads to a decrease in ILSS by 64% [1]. The tension-tension fatigue behavior remains unchanged with irradiation.

ITER has currently chosen a blend of 60% cyanate ester and 40% epoxy as a potting compound [10]. A hybrid is chosen to reduce the cost. Note that cyanate esters are quite expensive compared to epoxies. This combination was proposed by HUNSTMAN (more information can be obtained from www.huntsman.com). We should also look at this material for use in LARP magnets.

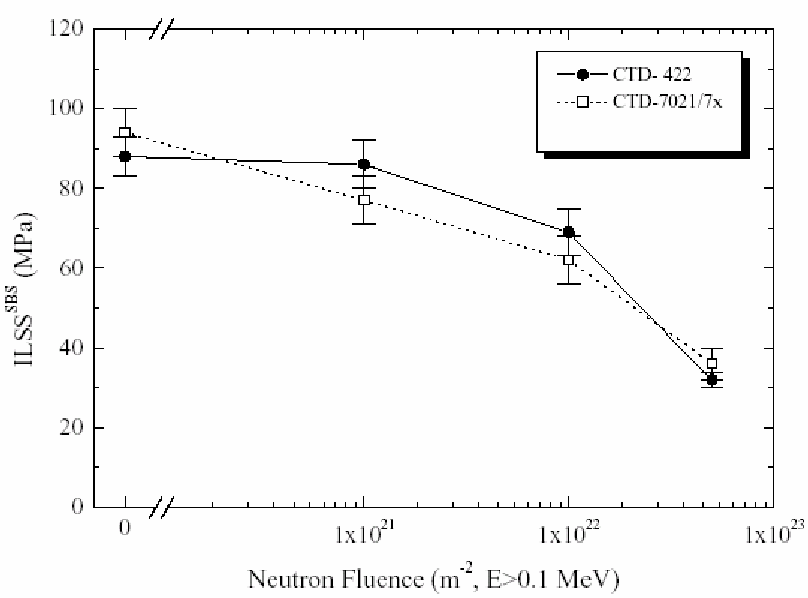

Fig. 3: *Interlaminate shear strength (ILSS) of the laminates measured at 77K as a function of the fast neutron fluence (E > 0.1 MeV) [1].*

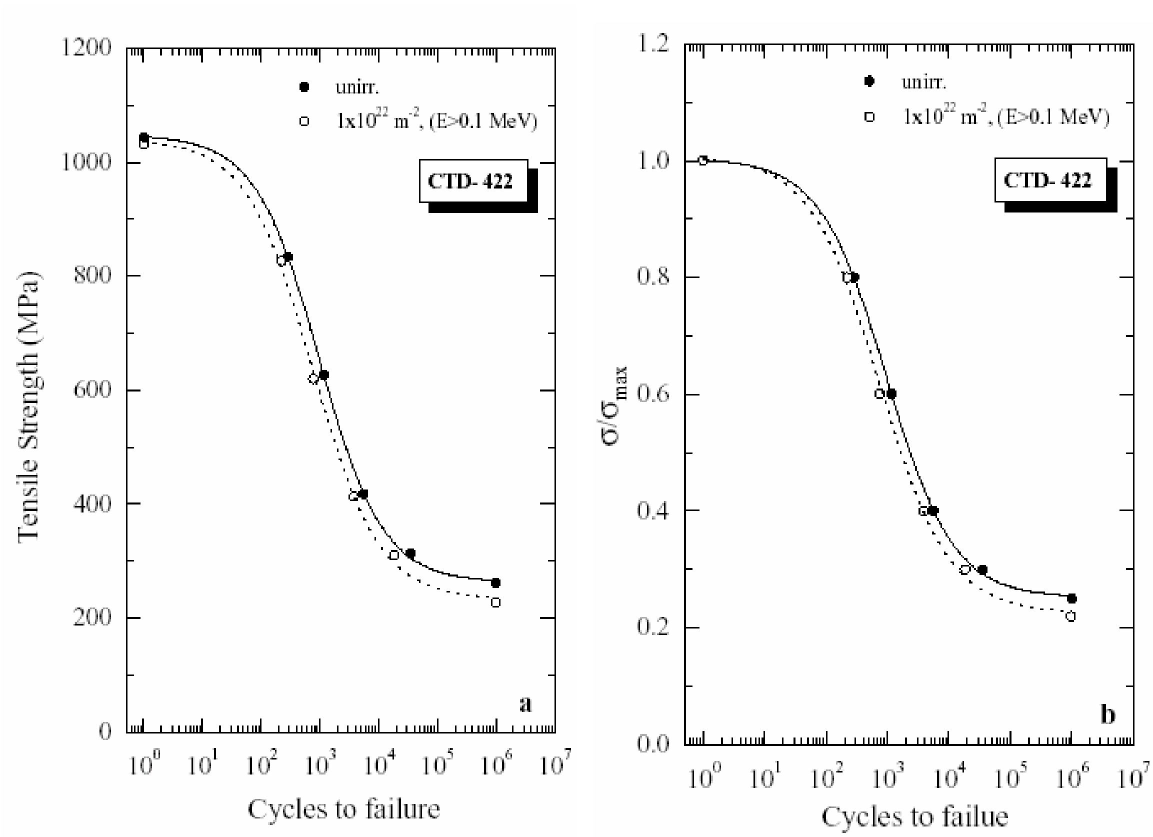

Fig. 4: *Absolute and normalized tension-tension stress-lifetime diagrams of the CTD-422 before and after irradiation to 1 x 10^{22} m^{-2} (E > 0.1 MeV) [1].*

4.3 Matrimid® 5292

Fermilab has recently looked into commercially available polyimides and/or bismaleimide resins for VPI. Matrimid 5292, a two-component bismaleimide system from VANTICO (a spin-off of CIBA-GEIGY and currently owned by HUNTSMAN) was identified as a possible candidate. Table 1 shows the properties of this compound as provided by the manufacturer. For comparison the epoxy CTD 101K, which Fermilab is currently using to impregnate the Nb_3Sn dipole coils has a viscosity of about 500 cps at 60 ^oC with a potlife of about 40 hrs.

Temperature, ^oC	Viscosity, cps	Potlife, min
75	5000	> 1000
100	800	1000
125	10	100
> 200	<10	< 1

Table 1: *Effect of temperature on viscosity and potlife of Matrimid.*

Ten-stack Nb_3Sn cable samples were reacted and then impregnated with Matrimid 5292 [9]. Impregnation was performed at 100 ^oC as it reduces the viscosity to 800 cps, which is sufficient for vacuum impregnation and also gives a potlife of 17 hrs sufficient to impregnate long production magnets. Fig. 5(a) shows a section of ten-stack sample impregnated with Matrimid. Fig. 5 (b) shows the mechanical behavior of the sample in the vertical direction. The properties are very similar to that of the sample impregnated with CTD-101K.

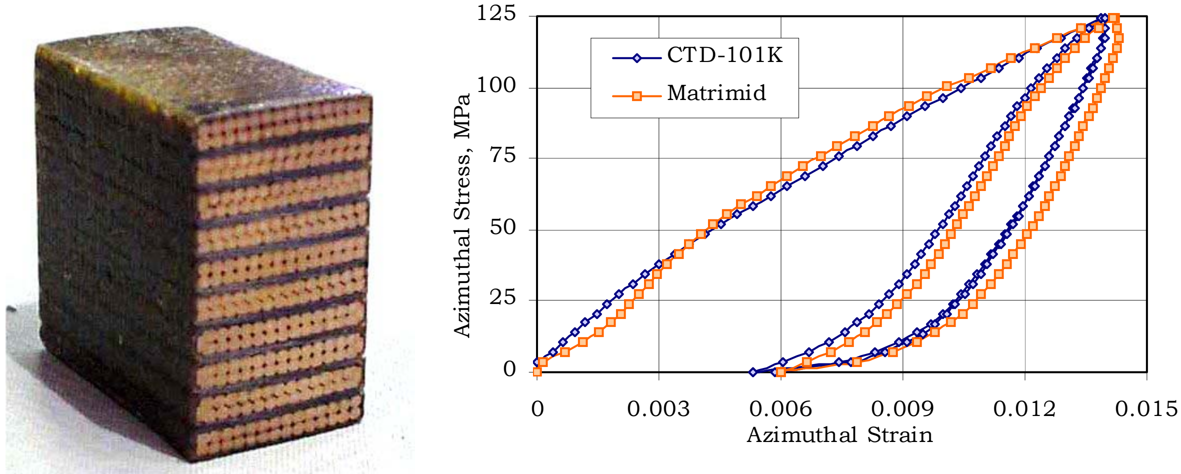

Fig. 5: *(a) Impregnated sample (b) Mechanical behavior in the vertical direction at 300 K [9].*

Ten-stack samples with alternate cables staggered were also reacted and impregnated for the purpose of high voltage tests. Fig. 6(a) shows the sample and the test data is shown is Fig. 6(b). Note that the cables were wrapped with 50% overlap ceramic tape, which amounts to an insulation thickness of 0.25 mm per cable.

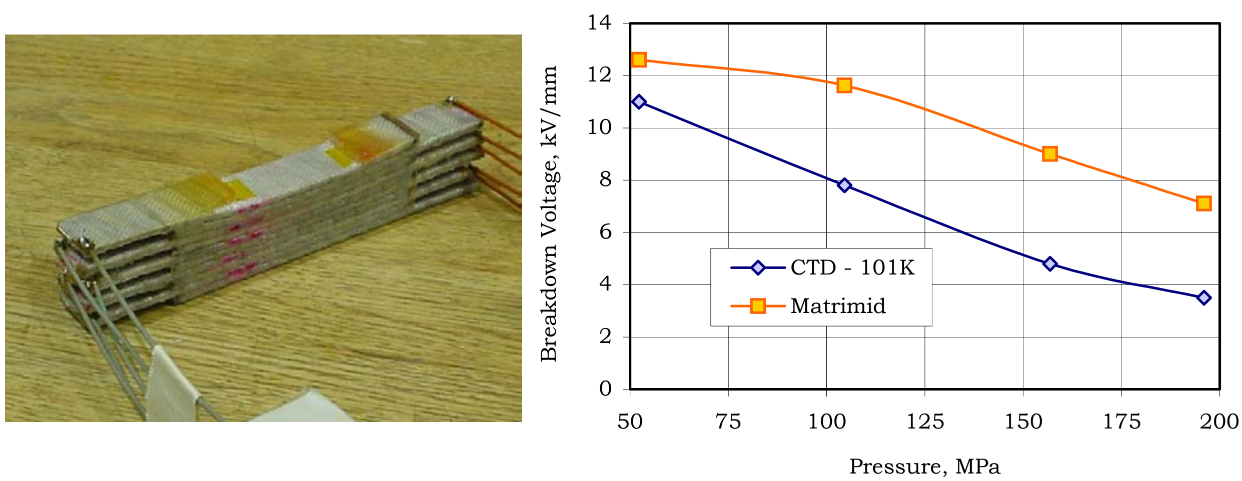

Fig. 6*: (a) Geometry of the sample used for measuring the dielectric strength (b) test data [9].*

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